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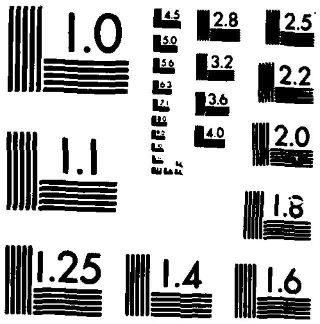

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Our Institute employs a three-stage approach to the problem of protecting the soldier from environmental extremes. This approach involves: (1) assessment of the heat transfer characteristics of the clothing and equipment as worn; (2) quantification of the effects of such factors as weight and placement of external loads, speed of walking and nature of the terrain to indicate energy release through mathematical equations; and, (3) predictions of physiological responses with time and alterations of the soldier or of his mission to minimize operational limitations. These computer predictions are conducted with a

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programmable calculator which provides output to indicate whether or not a given combination of work-rest cycles, activity level and environment will produce operational problems. The biophysical assessment of clothing heat transfer characteristics consists of evaluations of thermal insulation and the evaporative heat transfer characteristics of clothing items and systems. Measurements made on extremity items with copper hands (23 sections) and feet (28 sections) are employed in mathematical models to describe rates of extremit cooling in cold environments. Data obtained on a "sweating" copper manikin are used to indicate deficiencies in clothing design from a protection standpoint, and to assess the impact of items such as body armor and limited permeability coverings on evaporative cooling in the heat. Manikins have also been used to evaluate protection afforded by cold weather clothing systems, sleeping bags ar pads. Sophisticated infrared thermovision cameras are used to identify specifi areas of inadequate insulation in clothing items. Biophysical evaluations are carried out in small temperature controlled cabinets, the Institute environmental chambers, or the Climatic Chambers at the U.S. Army Natick Research and Development Center when winds or extremely low temperatures are required. The heated "sweating" copperman gives a direct measurement of the insulation provided by any clothing put on him, and its resistance to sweat evaporative cooling. The physiological assessment involves the study of volunteer soldier in environmental chambers or natural environments to obtain data on metabolic heat release and other physiological parameters related to thermal stress; and in realistic assessments of clothing, chemical protective, and auxiliary cooli or heating systems selected on the basis of copper manikin findings. Physiolo ical chamber studies have evaluated the effects of heat acclimatization, environmental condition and subject gender on a soldier's ability to perform work when dehydrated; and, armor operations during thermal stress with and without auxiliary cooling. Studies of physiological responses also include those with subjects immersed in water, nude or clothed. Facilities available to the Institute include a 3m x 3m x 4.2m (deep) thermally controlled pool in which heat exchanges from body core to skin have been studied on inactive or exercising men while immersed. This pool is also used to study various types anti-immersion and divers' suits using a waterproof copper manikin. The outpu of the Institute, in addition to research papers in the open literature, includes extensive provision of guidance to other DOD elements, other government agencies, NATO and industry on the limitations in tolerance of personnel on fo in land vehicular crew compartments and in aircraft. In tolerance limiting situations, changes in training, in clothing or equipment and/or in work-rest cycles and other measures designed to reduce heat or cold stress are frequentl recommended.

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CURRENT APPROACHES FOR THE BIOPHYSICAL AND PHYSIOLOGICAL EVALUATION OF COMBAT CLOTHING FOR ENVIRONMENTAL EXTREMES

FOURTEENTH COMMONWEALTH DEFENCE CONFERENCE ON OPERATIONAL CLOTHING AND COMBAT EQUIPMENT

AUSTRALIA 1985

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CURRENT APPROACHES FOR THE BIOPHYSICAL AND PHYSIOLOGICAL EVALUATION OF COMBAT CLOTHING FOR ENVIRONMENTAL EXTREMES

by

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C Institute employs a three-stage approach to the problem of protecting the soldier f.om environmental extremes. This approach involves: (1) assessment of the heat transfer characteristics of the clothing and equipment as worn; (2) quantification of the effects of such factors as weight and placement of external loads, speed of walking and nature of the terrain to indicate energy release through mathematical equations; and, (3) predictions of physiological responses with time and alterations of the soldier or of his mission to minimize operational limitations. These computer predictions are conducted with a programmable calculator which provides output to indicate whether or not a given combination of work-rest cycles, activity level and environment will produce operational problems. The biophysical assessment of clothing heat transfer characteristics consists of evaluations of thermal insulation and the evaporative heat transfer characteristics of clothing items and systems. Measurements made on extremity items with copper hands (23 sections) and feet (28 sections) are employed in mathematical models to describe rates of extremity cooling in cold environments. Data obtained on a "sweating" copper manikin are used to indicate deficiencies in clothing design from a protection standpoint, and to assess the impact of items such as body armor and limited permeability coverings on evaporative cooling in the heat. Manikins have also been used to evaluate protection afforded by cold weather clothing systems, sleeping bags and pads. Sophisticated infrared thermovision cameras are used to identify specific areas of inadequate insulation in clothing items. Biophysical evaluations are carried out in small temperature controlled cabinets, the Institute environmental chambers, or the Climatic Chambers at the U. S. Army Natick Research and Development Center when winds or extremely low temperatures are required. The heated "sweating" copperman gives a direct measurement of the insulation provided by any clothing put on him, and its resistance to sweat evaporative cooling. The physiological assessment involves the study of volunteer soldiers in environmental chambers or natural environments to obtain data on metabolic heat release and other physiological parameters related to thermal stress; and, in realistic assessments of clothing, chemical protective, and auxiliary cooling or heating systems selected on the basis of copper manikin findings. Physiological chamber studies have evaluated the effects of heat acclimatization, environmental condition and subject gender on a soldier's ability to perform work when dehydrated; and, armor operations during thermal stress with and without auxiliary cooling. Studies of physiological responses also include those with subjects immersed in water, nude or clothed. Facilities available to the Institute include a 3m x 3m x 4.2m (deep) thermally controlled pool in which heat exchanges from body core to skin have been studied on inactive or exercising men while immersed. This pool is also used to study various types of anti-immersion and divers' suits using a waterproof copper manikin. The output of the Institute, in addition to research papers in the open literature, includes extensive provision of guidance to other DOD elements, other government agencies, NATO and industry on the limitations in tolerance of personnel on foot, in land vehicular crew compartments and in aircraft. In tolerance limiting situations, changes in training, in clothing or equipment and/or in work-rest cycles and other measures designed to reduce heat or cold stress are frequently recommended.

1. INTRODUCTION

Concerned with studying the soldier, his clothing and equipment, the environment and the interactions which determine thermal stress in hot or cold environments, research studies are designed to provide a basis for predicting the soldier's physiological responses, performance decrements and tolerance times under a given combination of physical activity level, clothing and the environment. ~~Our~~ The current computerized prediction model considers the interaction of various multidisciplinary factors such as: (a) the theoretical physics of heat transfer, (b) the biophysics of clothing, (c) the physiology of metabolic heat production, distribution and elimination; and, (d) related meteorological parameters. Additional keywords: Army research.

Experimentation is currently conducted at five different interrelated levels of analysis. For instance, initially the physical heat transfer characteristics of uniform materials are determined by the use of classic heated flat plate theory and the "sweating" flat plate. Copper hands and feet are used to determine the heat transfer characteristics of selected handwear and footwear, respectively. Next, complete clothing ensembles are evaluated on a number of "sweating" copper manikins to determine the heat transfer characteristics of the particular clothing system. A newly developed articulated copper manikin will further allows us to quantify the importance of movement as it relates to the insulative values and evaporative impedance of various clothing systems. Determination of the insulation value (clo) and evaporative impedance value (i_m/clo) for various clothing systems helps provide important information relative to the thermal advantages or disadvantages of one system compared to another. The values obtained from these biophysical studies are used to establish a comprehensive data base to

ultimately enhance our computer predictions concerning the impact of clothing and/or equipment on soldiers' performance. Thirdly, large scale physiological trials under carefully controlled conditions are conducted in the US Army Natick Research and Development Center (USANRDC) Climatic Chambers with volunteer soldiers dressed in these clothing systems in an attempt either to validate or further refine our computer predicted tolerance limits from associated physiological responses. Next, small scale chamber studies are conducted in our Institute's climatic chambers to determine the effects of selected contextual factors (state of acclimation, physical training, sleep deprivation, level of hypohydration, etc.) on soldier performance under environmental extremes. Finally, experimentation with volunteer soldiers under environmental extremes is conducted during actual field operations. The findings from these studies allow us to establish a data base considering clothing characteristics, physical work level, state of acclimation, and environmental factors (dry bulb temperature, relative humidity, wind speed and cloud cover) with the express purpose of developing a comprehensive heat stress model for predicting soldier performance.

This paper presents an overview of our current approaches for the biophysical and physiological evaluation of combat clothing for environmental extremes. In addition, the concepts used to develop our heat stress model are discussed relative to predicting soldier performance considering the influence of the particular clothing and/or equipment, physical activity level and the environment.

2. BIOPHYSICAL APPROACH

a. Purpose

The biophysical assessment of clothing heat transfer characteristics, carried out by the Biophysics Branch, consists of evaluations of thermal

insulation and the evaporative heat transfer characteristics of clothing items and systems. Heat and moisture transfer characteristics are established for materials, clothing items and/or systems using heated "sweating" flat plates, copper hands and/or feet, heated copper manikins and infrared thermovision surface temperature analysis. Our Institute's biophysics program conducts clothing and equipment evaluations which are Tri-Service (US Air Force, US Navy, US Army) in scope and similar evaluations for some of the NATO countries.

b. Sweating Flat Plate

The physical heat transfer characteristics of uniform materials are evaluated through the use of classic heated flat plate theory and the "sweating" flat plate. Our guarded sweating flat plate has proportional control for three sections (test, guard and bottom). The guard and bottom sections are used to insure that all heat transfer is directed through the test section. The size of the test section for the guarded sweating flat plate is 0.056 m^2 which will generate a value for clo and allow evaluation of vapor impedence (i_m/clo) for the fabric or fiber being evaluated. The biophysical evaluations involving the guarded sweating flat plate are carried out in a small temperature and humidity controlled environmental unit. This environmental unit can control air temperature (T_a) from -7 to 49°C and relative humidity (rh) from 5 to 95%.

c. Copper Hand and Feet

Measurements made on extremity items are conducted utilizing one sectional copper hand and two sectional copper feet. The copper hand can evaluate twenty-three thermally isolated sections to give total and sectional clo evaluations but does not allow evaporative transfer capability. Each section is manually adjusted to the desired set-point temperature. Thus, the

total and individual clo determinations for various sections of a handwear item can be quantified to ascertain areas of insufficient insulation.

Two sectional (28 sections each) thermally isolated computer controlled copper feet (right and left foot) are used for evaluation of total and individual clo determinations of footwear items. These copper feet allow us to determine selected areas for either foot where insulation may be inadequate. However, they do not presently allow evaporative transfer capability.

d. Copper Manikins

Our Institute employs the services of eight copper manikins. Four of these manikins are single circuit in design and capable of determining overall clo and the evaporative transfer properties (i_m value) of the particular clothing ensemble. Three of these manikins are 177.8 cm high and provide a surface area of 1.86 m^2, while the fourth is 170.2 cm high and provides a surface area of 1.68 m^2 to simulate the average size woman. Of the three similar manikins (177.8 cm, 1.86 m^2), one is used as our standard for static clothing studies, another is waterproofed for immersion studies, while the third is currently being converted to DC power to provide twelve independent computer controlled zones. This will allow surface pattern temperature control to directly simulate skin temperature as a function of physical activity level which no other manikins in the US do at present.

Two additional manikins each have fifteen individual heating zones. One manikin stands 170.2 cm high with a surface area of 1.68 m^2, while the other is seated with the same surface area previously mentioned. Both of these manikins determine overall clo but have no evaporative heat transfer capability.

Our seventh manikin has six sections with thermal barriers between sections to provide total clo and i_m of a clothing ensemble in addition to

individual sectional evaluations of the head, torso, arms, hands, legs and feet. This manikin is used most often in association with our microclimate clothing ensemble evaluations in support of USANRDC. Our newest manikin which has nineteen zones is articulated and stands 177.8 cm high with the surface area of 1.68 m^2. This surface area can vary somewhat with flexing of the arms and legs associated with movement. Zone temperatures will be computer controlled with DC power supplies. This articulated manikin has a range of walking speeds from standing to 1.56 $m \cdot s^{-1}$. In conjunction with these manikins, sophisticated infrared thermovision cameras have been used to measure the surface temperature of clothing systems to help detect areas of greater heat loss.

e. <u>Recent Accomplishments</u>

The major accomplishments of this biophysics program for fiscal year (FY) 84 are as follows: (a) evaluation of arctic survival sleeping bags, extended cold weather sleeping bags and US Marine Corps sleeping bags; (b) biophysical assessment of petroleum oil lubricating (POL) gloves for field use, selected handwear items from USANRDC and selected cold weather handwear; (c) further biophysical evaluation of standardized combat boots; (d) biophysical evaluation of US Air Force aircrew survival vests and USANRDC aircrew survival vests with armor; (e) biophysical assessment of tank air-cooled vest and the integrated air-cooled vest for armored vehicle crewmen; (f) evaluation of chemical warfare prototype suits and standard uniforms for US Marine Corps; (g) biophysical evaluation of selected NATO combat clothing and equipment; and (h) evaluation of Israeli chemical warfare protective fabrics.

3. PHYSIOLOGICAL APPROACH

a. Purpose

The physiological assessments conducted by our Institute involve the study of volunteer male and/or female soldiers in environmental chambers or natural environments to obtain information on metabolic heat release and other physiological responses related to thermal and/or exercise stress. Human physiological studies are conducted in the large USANRDC Climatic Chambers, the smaller climatic chambers of our Institute and during actual field operations.

b. Large Scale Physiological Trials

Large scale physiological trials are conducted under carefully controlled environmental conditions in the USANRDC Climatic Chambers. These Climatic Chambers encompass an Arctic Wind Tunnel and a Tropic Wind Tunnel with the test area of each being 4.6 m x 19.8 m. Each of these wind tunnels includes two 4-man exercise treadmills for marching on the level or with grade elevation capabilities of 12%. The Tropic Wind Tunnel allows air temperature to be controlled from - 18°C to 74°C with humidity control from 18 to 90% rh and wind velocity from 0.9 to 18 $m \cdot s^{-1}$. Water spray can be controlled at a rate of 10.2 cm per h. The Arctic Wind Tunnel can be climatically controlled within a range of -57°C to 21.8°C with humidity, wind and water spray capabilities similar to the Tropic Wind Tunnel.

Standard physiological measurements during these experiments involve deep body temperature (esophageal or rectal temperature), mean weighted skin temperature ($\bar{T}_{sk}$), skin dew point temperature (T_{dp}), heart rate (HR) and oxygen uptake ($\dot{V}O_2$). Total body sweat rate ($\dot{m}_{sw}$) is calculated from nude body weight loss adjusted for water intake and urine output. In many of these experiments, venous blood samples are collected to allow measurement of

hemocrit, hemoglobin, plasma lactate, plasma osmolality, plasma electrolytes, plasma oncotic pressure and plasma hormones. Deep body temperature, $\bar{T}_{sk}$ and HR can be plotted for each subject at two min intervals using a Hewlett-Packard 9825-A computer and 9862-A plotter. Most of these experiments involve the simultaneous testing of 8-10 soldiers during a given experimental evaluation, and on some occasions, two groups (16-20 soldiers) evaluated during a given work day.

c. Small Scale Chamber Studies

Our Institute provides fourteen environmentally controlled rooms which are collectively capable of providing controlled temperatures from -40°C to 60°C with control of relative humidity from 10 to 98% and wind velocity capabilities up to 3.0 $m \cdot s^{-1}$. Chambers typically used for human experimentation range from 2.7 m x 3.6 m to 7.3 m x 5.0 m. In addition to the physiological responses which are measured during the large scale physiological studies, a number of other measures can be easily made during these small chamber studies. For instance, measurement of forearm blood flow (FBF), cardiac output ($\dot{Q}$), central venous pressure (CVP), total body water (TBW), and determination of the extracellular fluid volume (ECF) can be routine. In addition to determination of total body sweat loss, local sweating can be determined through the use of automatic dew point temperature sensors. Usually, these small chamber experiments involve the test evaluation of one subject at a time.

Facilities are also available for water immersion studies in a thermally controlled pool which is 3 m x 3 m x 4.2 m (deep). This immersion facility holds 36,000 liters of water and can control the water temperature between 5

and 45°C. In addition to rest or exercise experiments on soldiers (either nude or clothed), this pool is also used to study various types of anti-immersion and divers' suits for the US Navy and US Air Force using our waterproof copper manikin.

d. Studies During Actual Field Operations

Many of our computer predictions of physiologically based tolerance limits are validated from observations of research studies during field operations. Most of these studies in the field involve a limited number of actual physiological measurements. For instance, rectal temperature, $\bar{T}_{sk}$, HR and $\dot{m}_{sw}$ are the most routine in addition to our standard environmental measurements. Most recently, our field studies have involved experimentation concerning microclimate cooling as compared to no auxiliary cooling in chemical protective clothing for soldiers in armored vehicles.

e. Recent Accomplishments

The major accomplishments of this physiology program for FY84 are as follows: (a) three large scale laboratory studies completed to examine different prototype microclimate cooling systems for reducing heat strain in soldiers; (b) large scale studies conducted evaluating the physiological effects of three hypohydration levels on soldiers' ability to tolerate exercise-heat stress; (c) small scale studies completed examining the influence of sleep deprivation on an individual's ability to thermoregulate while performing physical exercise; (d) small chamber projects completed examining the effects of human heat acclimation on skeletal muscle metabolism; (e) small chamber research published which examines exercise limiting factors and thermoregulation for upper body exercise as well as the ability of women to perform upper body exercise; (f) water immersion facility studies on human cold

acclimation; and, (g) completed field studies at Yuma Proving Grounds (Yuma, Arizona), Tropic Test Center (Panama City, Panama) and Fort Knox (Radcliff, Kentucky) concerning the physiological impact of tank crewmen wearing chemical protective clothing and/or microclimate cooling during exercise-heat stress.

4. COMPUTER PREDICTION MODELLING

Over the last two decades, the US Army Research Institute of Environmental Medicine has been establishing the data base and developing a series of predictive equations for deep body temperature, HR and $\dot{m}_{sw}$ responses for clothed soldiers performing physical exercise in various environmental extremes. This resulted in predictive equations for rectal temperature (2), HR (3) and $\dot{m}_{sw}$ (11) as a function of the physical exercise intensity, environmental conditions and particular clothing ensemble being published in the open literature. In addition, important modifying factors such as energy expenditure (6), state of heat acclimation (4) and solar heat load (1) have been evaluated and appropriate predictive equations developed. Suitable data bases to evaluate the predictive importance of cardiorespiratory physical fitness (5,9), gender (7,10) and state of hydration (7,8) have been established.

Over this same time period, our Institute has attempted to program these predictive equations on various desk-top and hand held calculators with the express purpose of developing a comprehensive heat stress model for predicting soldier performance to physical exercise, clothing and the environment. Hopefully, military users can employ these equations to help avoid unnecessary casualties associated with these environmental heat extremes, and by predicting appropriate work-rest cycles and water requirements facilitate the achievement of mission objectives.

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